CONFERENCE PROCEEDINGS

Leakage Pathways from Potential CO_2 Storage Sites in the Texas Gulf Coast and Implications for Permitting

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Abstract

The Texas Gulf Coast is an attractive target for carbon storage. Stacked sandstone and shale layers provide large potential storage volumes and defense-in-depth leakage protection. Using simple geological mapping and oil and gas analogs to characterize likely CO_2 traps, we analyze their statistical distribution and determine the likely pathway and contacted volume of a migrating plume. We also explore, with a numerical model, the geometry of a plume as a function of formation parameters. We investigate the particular nature of most faults in the Gulf ("growth faults") and their impacts, both positive and negative, on CO_2 containment. In addition, multiple perforations resulting from intensive hydrocarbon exploration and production have weakened seal integrity in many favorable locations. Even wells abandoned to current standards cannot be guaranteed leak-free in the long term, although shale heaving may reduce the problem. We describe spatial and other statistics extracted from State Agency databases as applied to carbon storage.

The specific character of the geological confinement in the Gulf region has a profound impact on the permitting process including definition and size of the Area of Review, definition of the injection zone, maximum amount to be safely injected in a given trap, and location of monitoring wells if any. An option, viable for the Texas Gulf Coast as well as other regions, to reduce geologic uncertainty and risk on ground water resources, to decrease the impact of wells, and to limit the amount of information to be collected, is to inject CO_2 below the maximum penetration of most wells.

Introduction

Geological sequestration of CO_2 (also called carbon storage) has been recognized as an important way to mitigate increase in atmospheric CO_2 (IPCC, 2005, Chapter 5) and has been touted as a way to address global warming. Injection of CO_2 has the additional benefit of aiding in oil recovery (Enhanced Oil Recovery, EOR), as well as enhancing coalbed methane recovery (ECBMR) because CO_2 sorbs more strongly to coal than methane does. Legislation and regulations for EOR and ECBMR are already in place addressing important operational issues of the injection phase. This study focuses on some of the technical underpinnings relating permitting to long-term (hundreds to thousands of years) postclosure migration of CO_2 in the subsurface, using the Texas Gulf Coast as an example. The emphasis on Texas is appropriate because of the abundance of saline aquifer candidates in the Texas Gulf Coast (Hovorka et al., 2000), and because about 40% of the electric power in Texas is generated by coal-fired power plants often located above those formations. Another reason to focus on the Gulf Coast is that many reservoirs are susceptible to CO_2 flooding (Holtz et al., 2001). Historically, for a variety of reasons (e.g., CO_2 availability via pipelines primarily developed to the Permian Basin), most CO_2 floods in the state have taken place in West Texas and far fewer in the Gulf Coast. The Texas lignite belt is also located in the Gulf Coast area but farther inland. The concept of stacked storage makes it likely that CO_2 captured from coal-fired power plants could be transported through a pipeline toward the coast, where they are most likely to be used. Another, secondary reason for focusing on the Texas Gulf Coast is that it has a very low level of seismic activity and is not a credible candidate for any type of volcanic or tectonic activity in the near future.

Central to all industrial projects is the permitting process, particularly its cost and what it involves in terms of time investment. The current regulatory framework covers all aspects of the injection phase with two goals: to protect the water resources and to protect hydrocarbons and other resources that could be produced in the future (e.g., geothermal energy). Any CO_2 storage project needs to address these two issues, but in addition it must guarantee that CO_2 will be reasonably sequestered in the long term in order to be effective in obtaining the reduction in atmospheric concentrations. This latter requirement could translate into additional constraints in the permitting process or additional assurance required to make the CO_2 credits fungible.

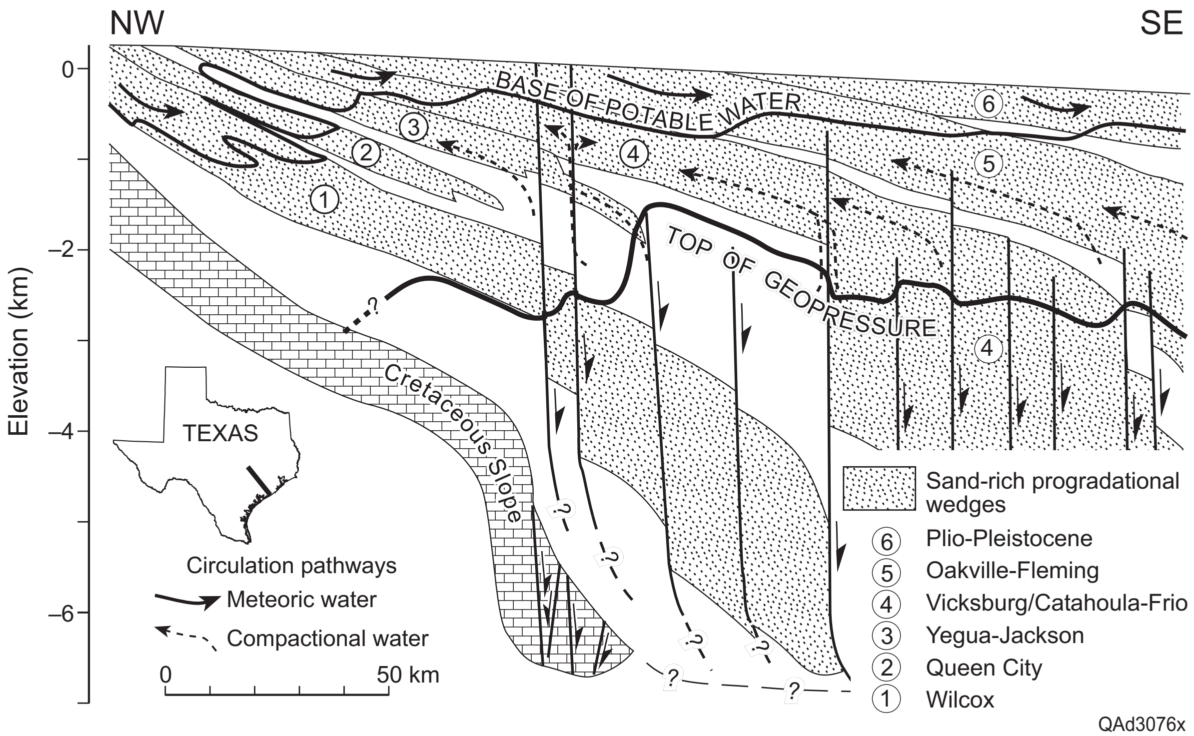
Underground Sources of Drinking Waters (USDW) are the most likely resources to be impacted by unintentional CO_2 leakage. Conduits for leakage to USDW can be natural (faults or updip sections or injection formations) or human made (wells). Injection pressure is the driving force behind leakage during hydrocarbon reservoir water flooding or UIC Class I waste (hazardous or not) disposal, and mainly faults and wells are of concern. In the case of injection of a buoyant fluid, such as CO_2, gravity forces continue acting, even after dissipation of the pressure pulse. This phenomenon adds a third avenue for leakage, upward connectivity of transmissive zones through, for example, loss of seal integrity, sand-against-sand fault compartments, or spill points where faults die off.

Underground carbon storage modes, or trapping mechanisms, can be distributed among four main categories: (1) residual or capillary trapping owing to multiphase flow processes, (2) solubility trapping through the dissolution of CO_2, (3) structural trapping, and (4) mineral trapping due to the reaction of CO_2 with host rocks. Several studies have suggested that mineral trapping, although representing the ultimate fate of CO_2 in the subsurface, is a slow process and that in a hundreds to thousands of years timeframe, the main trapping mechanisms are capillary and hydrodynamic. Solubility trapping can be volumetrically significant and rapid but may be limited by surface area between water and CO_2 in some injection geometries. In most cases, solubility trapping appears to be a minor component of the total storage although the induced water density contrast may alter flow dynamics and improve CO_2 trapping through dissolution into the saline formations. The capillary trapping mechanism does not perform well if the CO_2 path is cut short intrinsically by fingering or by external features, such as a well or a conductive fault.

Carbon Storage Site Configuration along the Texas Gulf Coast

Texas Gulf Coast Geology

A good understanding of CO_2 leakage entails a good knowledge of the local geology, and the general geology of the Gulf Coast is simple, albeit complicated in the details. It consists of a thick Tertiary and Quaternary wedge (several kilometers) of alternating sandy and clayey layers resulting from the deposition by rivers of their sediments in deltas and farther out in the ocean in multiple, offlapping cycles that record deltaic and shoreface progradation (Figure 1). The process, resulting in fluvial, deltaic, barrier bar/strandplain, and slope/basin depositional systems such as those of the modern Mississippi River and smaller, coastal rivers, is still active today.



Note: Adapted from Galloway (1982) and Galloway et al. (1982)

Figure 1. Southern Gulf Coast major sand-rich progradational packages and growth fault zones beneath the Texas coastal plain. Wedges of interest for carbon storage are #4 (Vicksburg/Frio) overlaid by a regional seal (Anahuac Shale, white wedge between #4 and #5) and #5 (Oakville/Fleming) overlaid by another regional seal (*Amphistegina B* Shale, white wedge between #5 and #6) complementing the low permeability of the upper half of the wedge (Burkeville confining system). The last major progradation wedge of plio-pleistocene age (#6) is still active and is too shallow to be of prime interest for CO_2 storage.

Growth faults, resulting from sediment loading on unstable substrates, periodically develop. Intermittent movement along these growth faults has accommodated accumulation of enormous masses of sediments. Growth faults are mostly syn-deposition faults (still active in the Houston area on sediments of wedge “6” of Figure 1) but could be reactivated at a later time. They are mostly restricted to sand-rich formations and die out in some thick clay formations. It follows that growth faults are typically limited to the formation they impact and generally do not extend to the surface (Figure 2). Growth faults are characterized by a thickness asymmetry on each side of the fault because sediments continue accumulating on the downthrown compartment of the fault. Closed structures, ideal to trap fluids and called roll-over anticlines, are often times created by the movement of the fault (e.g., Figure 3).

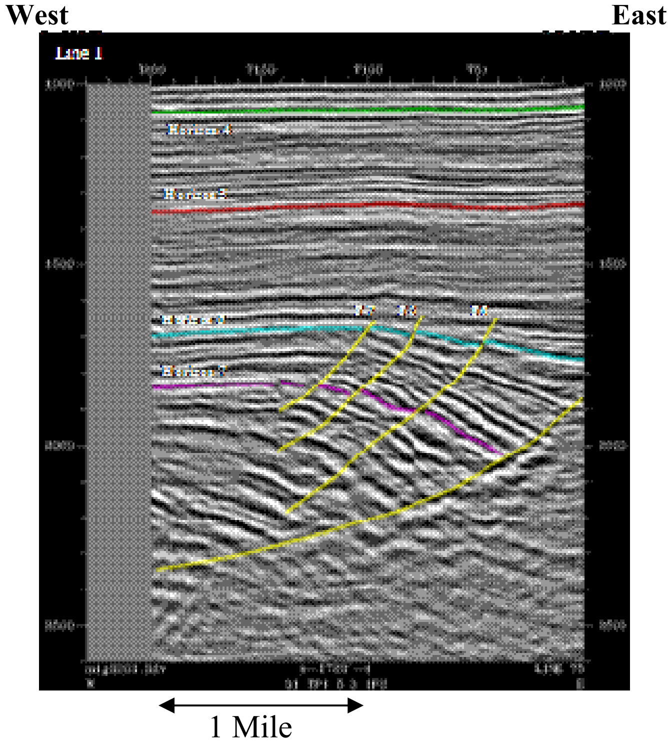


Figure 2. Example of growth fault (inclined yellow lines) in the Southern Gulf Coast as evidenced by a seismic survey

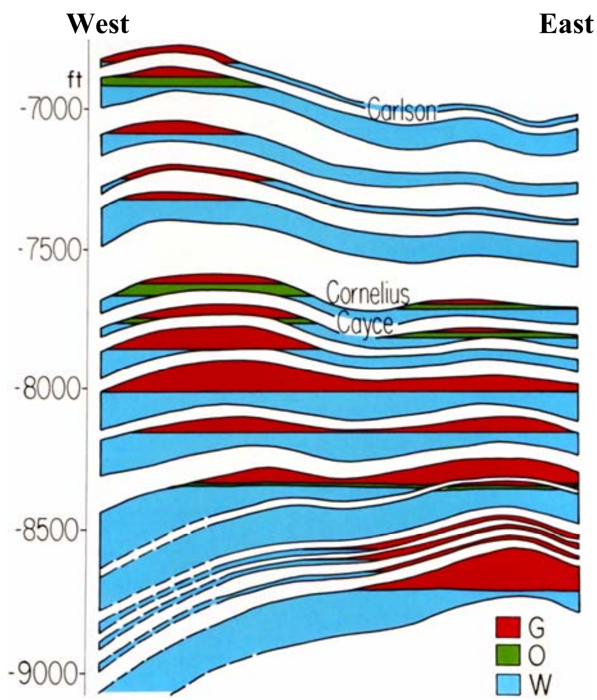
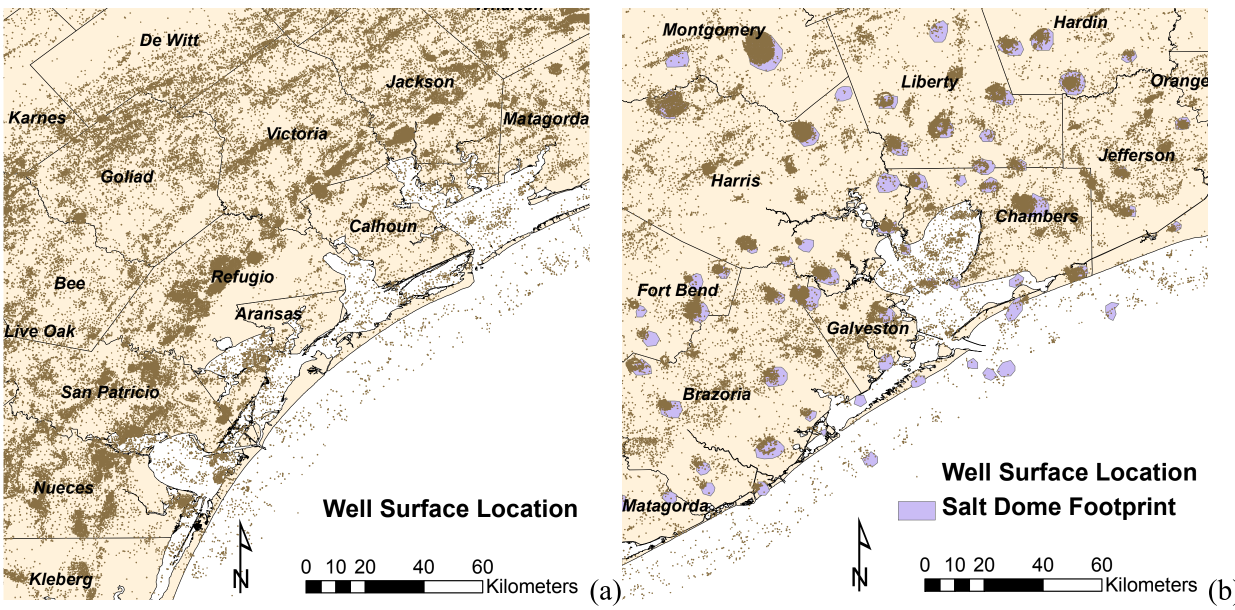


Figure 3. West-East strike-oriented cross-section of the double-crested roll-over anticline that forms the Markham North-Bay City North field in Matagorda County, Texas. This is a very large gas play with some large oil reservoirs (Carlson, Cornelius, Cayce) (from Tyler and Ambrose, 1985). It represents a common type of trap in the Gulf Coast.

Closed Traps

Despite a general gentle dip toward the Gulf of Mexico, local geometry of the layers does include numerous structural traps, owing to the activity of growth faults and radial faults around salt domes and to the deformation near diapirs. Hydrocarbon traps represent good analogs for closed CO_2 traps. They occur in areas where these sediments have been tilted or deformed within anticlinal structures bounded by growth faults. Deformation of strata above the kilometer-thick Jurassic Louann salt layer has resulted in a contrast in types of structural traps. In the northern section of the Texas Gulf Coast, salt movement has been focused around piercement diapirs, resulting in numerous and complex traps associated with locally steeply dipping strata. Farther south, regionally aligned reservoirs in the Corpus Christi area are more commonly created by structural and stratigraphic traps along growth faults. This contrast in trap style is visible on a map of oil and gas well surface locations, which are clustered around salt domes in the Houston area and more spread out elsewhere (Figure 4).



Source: RRC "Well" database

Figure 4. Surface well location in the Corpus Christi-Victoria area (a) and in the Houston area (b). Note the contrast in style between the Houston area where a significant fraction of wells and hydrocarbon traps are related to salt domes and the Corpus-Christi-Victoria area where salt domes are deeper or inexistent. More than 100,000 well locations are displayed.

Open Traps

Within the range of buoyancy of most hydrocarbons (more than oil, less than gas), CO_2 will also follow similar pathways and accumulate in similar traps as described in the previous section. However, if the injected volume is larger than the capacity of the first encountered trap, CO_2 will continue to flow upward until it reaches another trap, leaving behind a trail at residual saturation (Figure 5 and Figure 6). It follows that closed traps are charged with CO_2 with water at residual saturation while open traps consists of the trail of the CO_2 plume at residual saturation. Relying on capillary trapping will work well if the two other avenues for leakage, wells and faults, can be shown to impact the behavior of the storage site only minimally.

Capacity of an open trap depends on the heterogeneity of the injection formation and on that of the overlying layers. Potential subsurface storage sites in sedimentary basins fall into a large range of geological heterogeneity. The 300+ meter-thick marine Utsira Sand of Miocene age at the Sleipner site has been interpreted as a relatively homogeneous graben fill of fine sand with very thin but laterally extensive intercalations of a shaly nature and overlain by several massive shales (Chadwick et al., 2004). On the contrary, the Gulf Coast area displays a high level of heterogeneity, condition particularly favorable for containing leakage from the main storage area and promising as an overall attenuation process. The question of the migration mode, between the end-members of a wide diffuse spreading and of a localized fingering/channeling, remains open although all indicators point to a limited role for fingering (e.g., Kumar et al., 2004).

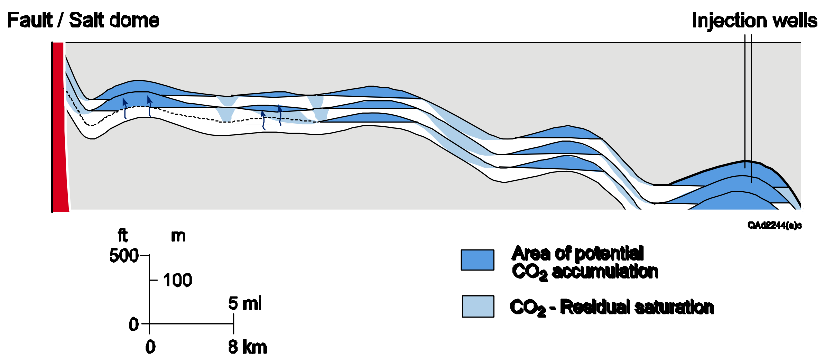


Figure 5. CO_2 travel path and trapping mechanisms. Both closed traps where water is at residual saturation and open traps where CO_2 is at residual saturation are shown.

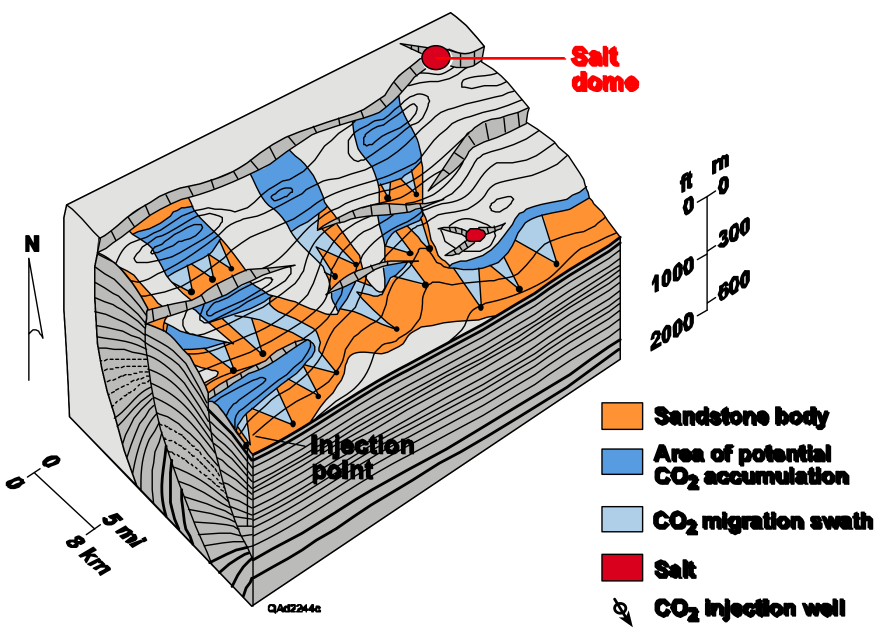


Figure 6. Example of CO_2 migration in a typical Gulf Coast setting. Sand bodies are typically fluvial channels or deltaic accumulations. CO_2 migrating upwards fill up closed traps and leaves a trail at residual saturation between them. Closed traps are often well-expressed next a growth fault.

Using a contour map of the top of the Frio (base map purchased by Geomap, Dallas, TX), traps and their fetch area were mapped (Figure 7). Large areas remain blank, not because they lack traps, but because they ultimately lead to a salt dome. A statistical analysis of the distribution of closure and fetch areas is presented in Figure 8. A significant number of traps have an area smaller than 5 square miles but some are very large covering tens of square miles. The associated capacity is, in most cases, less than 10 millions tons of CO_2. Traps are generally limited in volume by the limited lateral extend of the growth fault. Injecting more CO_2 into the trap will result into the spilling of the additional volume at the edges of the trap from which it will move to the next trap leading to a process that can be described as "fill and spill".

Multiple similar maps can be produced for the main formations of the Gulf Coast, with variations from the example presented both because of faults tapering off with depth and toward the surface and because of the increased impact of salt domes with depth.

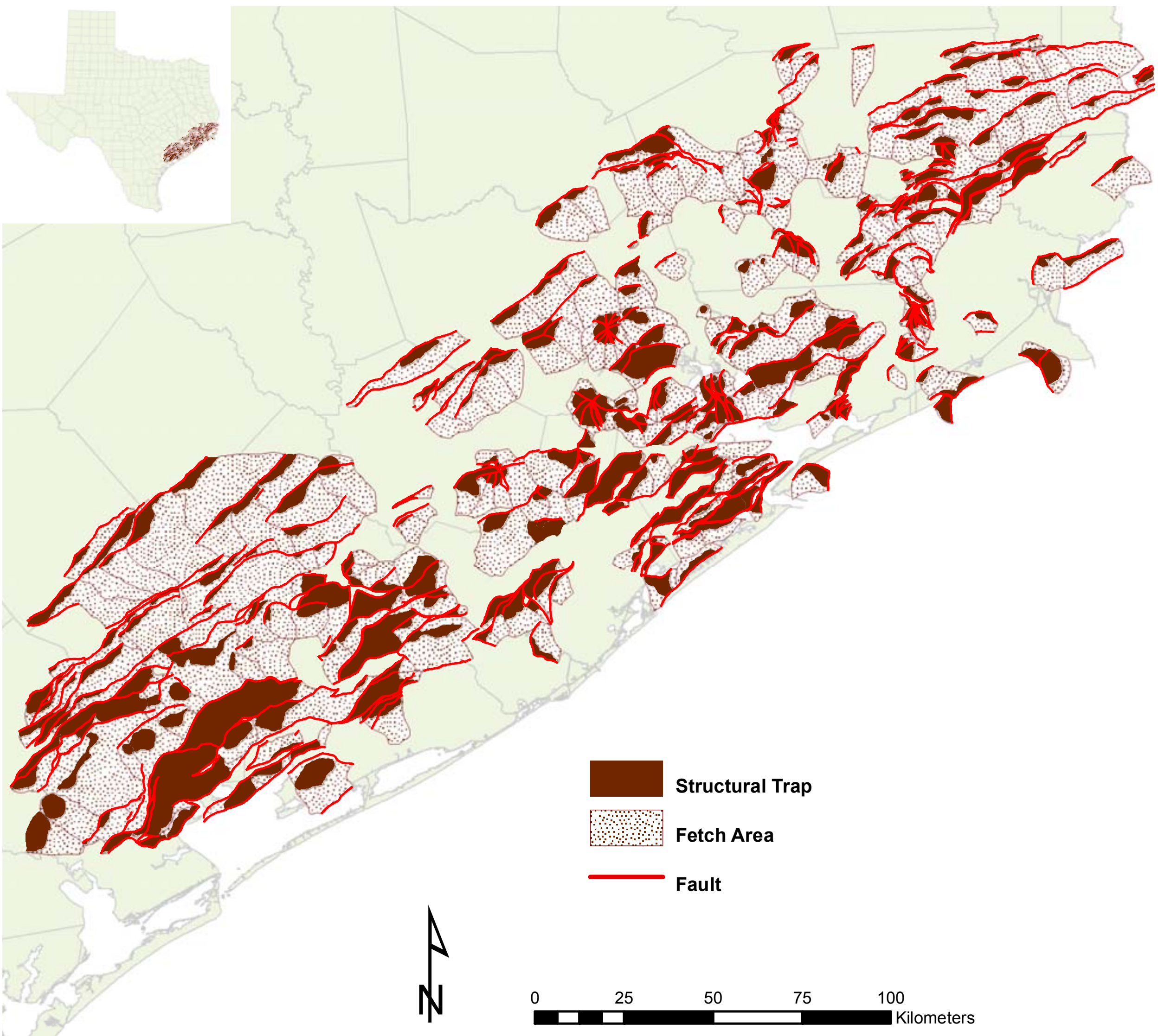
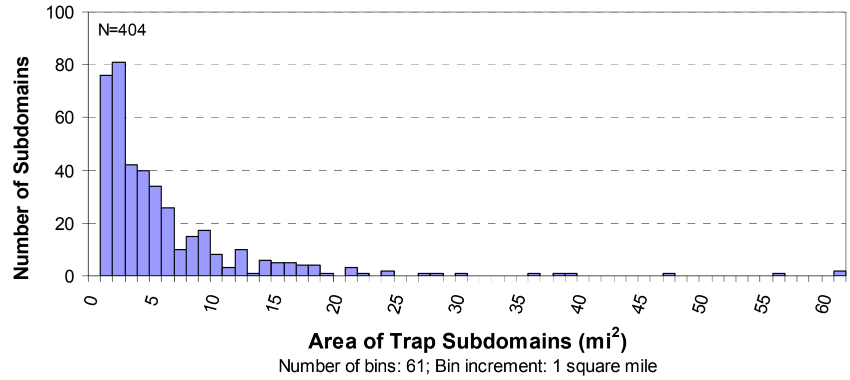


Figure 7. CO_2 trapping on top of the Frio or equivalently beneath the base of the regional seal (Anuhuac Shale). Closed structural traps abut on growth faults while each open trap ("fetch areas") located downdip of the associated closed trap (more than one fetch area can lead to a single closed trap). Areas left in background color eventually lead to a salt diapir and are not primary targets for CO_2 injection.



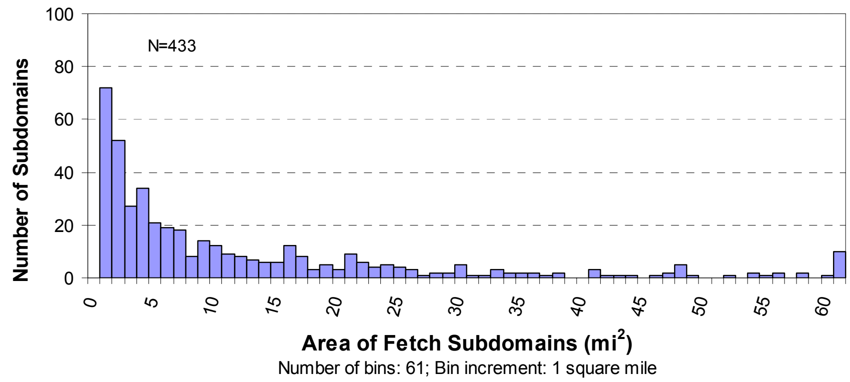


Figure 8. Statistical distribution of trap and fetch subdomain footprints. Bin values on the horizontal axis should be understood as "less than" except the last bin which represents the number of subdomains >60 mi^2.

Tentative Calculation of Closed Trap Capacity

The distribution of closed trap capacity can be determined by either collecting information from existing oil accumulations in the Texas Gulf Coast (Figure 9) or by making assumptions on the shape and characteristics of the closed traps defined in the previous section.

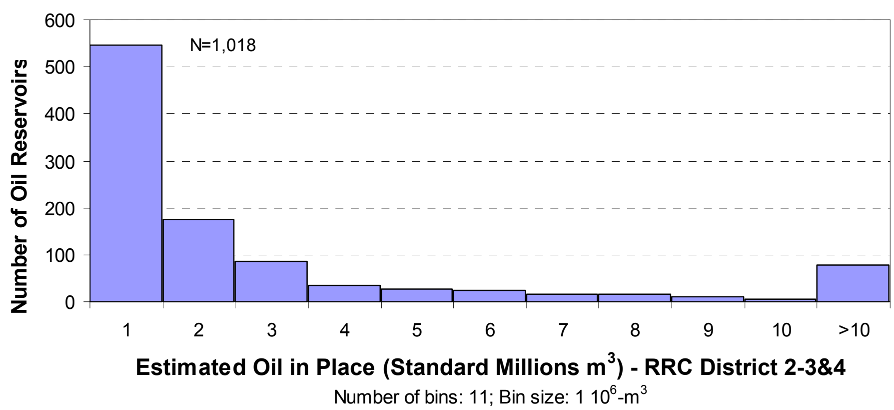


Figure 9. Distribution of estimated oil in place in Texas Gulf Coast reservoirs. It represents an analog to the distribution of closed trap size that can be expected for CO_2 storage (data from Nuñez-López and Holtz, 2006)

A crude computation of the trap capacity (Figure 10) can be performed by assuming that the CO_2 density is 700 kg/m^3, that the sand porosity is 30%, that the sand fraction is 30%, that the area is cone-shaped (1/3 of the product of the area by the height), and that the gas saturation is 80%. The trap height was also measured and extracted from the contour maps. Figure 10 suggests that most traps will not hold more than 10 million tons of CO_2, amount smaller than the lifetime output of a typical power plant (5 million tons a year for 30 years). Multiple injection levels each corresponding to a closed structure can be engineered. Another engineering option would be to inject in the deepest structure and take advantage of capillary trapping as well as dissolution trapping as the plume travels upwards.

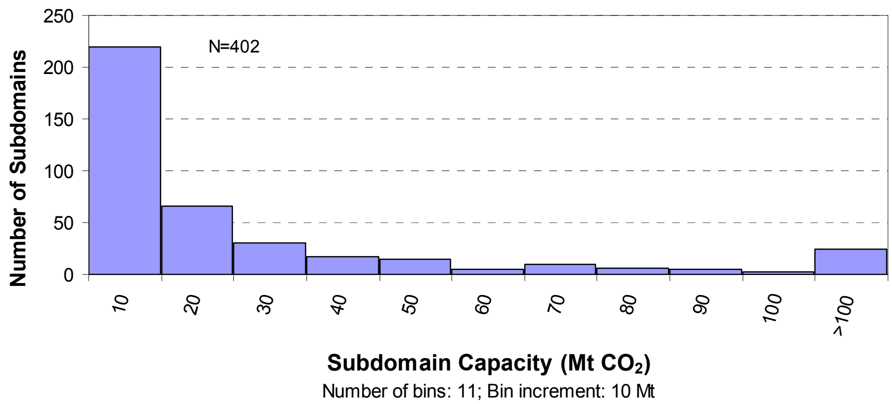


Figure 10. Tentative distribution of capacity of trap subdomains (i.e., closed traps). Bin values on the horizontal axis should be understood as "less than" except the last bin.

Tentative Calculation of Open Trap Capacity

Calculation of the open trap capacity involves understanding the amount of spreading resulted form leakage/injection from a single point. A scaling analysis suggests that the aspect ratio a of the plume is mainly function of the permeability ratio and of the dip angle θ: $a = \frac{z_0}{x_0} \sim \frac{k_z}{k_x} \cot\theta$

Permeability ratios are relatively well known at the core level (Holtz, 2003) and represent an upper bound to the permeability ratio at the reservoir scale because fractures are not commonly described in Texas Gulf Coast reservoirs. Residual saturation in the Gulf Coast formations as a function of the porosity is also known (Holtz, 2005). Knowledge of (1) trap geometry and spatial arrangement, (2) permeability and porosity distributions and their empirical functional relationship with gas residual saturation, and (3) leaking plume shape will allow quantification of the capacity of Gulf Coast formations to absorb the "spill" part of plume migration. Preliminary results show that the capillary trapping mechanism can sequester 1 to 10% of the amount trapped in a single closed trap in an average "fetch area".

Leakage Pathways

Oil and Gas Fields and Wells

Three main variables relate to well leakage (for all wells, that is, injection, production, and exploratory wells, dry holes, core holes…): well density (how many wells per square area), well depth (how deep the well is and in which formations the completion intervals are), and well age (an older well being more likely to experience leaks in the near term because environmental rules have become progressively stricter in the 20th century). Approximately 140,000 known wells exist in the Tertiary section of the Gulf Coast between Corpus Christi and Houston. About 30% are abandoned wells with plugging records available in electronic form from the Texas Railroad Commission (RRC). The remainder comprises of either wells still in operation or wells with no records or records available only in microfilm or paper form. Well density can be extremely high around salt domes, hundreds or even thousands of wells per square kilometer (1 km^2 ~250 acres) (Figure 10).

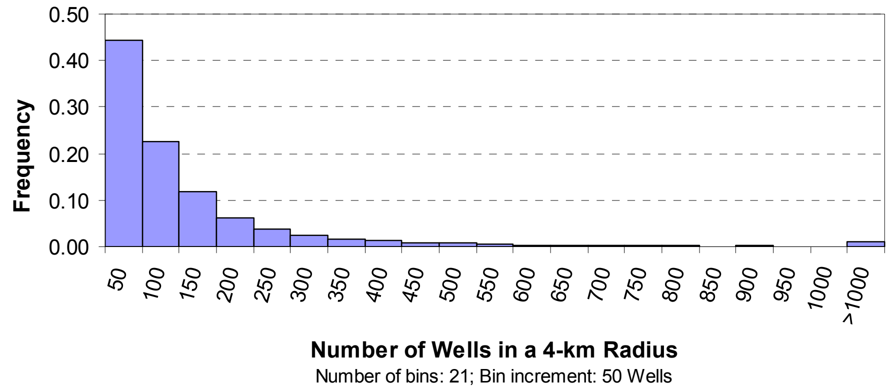


Figure 11. Distribution of well density in the Gulf Coast area (4 km = 2.5 miles). Bin values on the horizontal axis should be understood as "less than" except the last bin

A Short History of Well Drilling, Plugging, and Abandonment in Texas

Following Warner et al. (1997), the RRC well dataset can be sorted into four classes: post-1983, 1983–1967, 1967–1935, and pre-1935, arranged in decreasing order of reliability relative to leakage. The general trend in the past century has been to drill deeper and tap deeper hydrocarbon accumulations (Figure 12). The number of fields discovered closely follows production. Oil and gas production peaked in the 1960's followed by a slump in the 1970's, then by another peak in the 1980's, followed by a decrease than still continues today. The year 1934 saw the first specific plugging rules. They required that the producing formation be plugged with recirculated cement. Before that date, although regulations had existed since the beginning of the century, they were unevenly enforced. The years 1967 and 1983 were also marked by major improvements of well-abandonment rules (Figure 13). Warner et al. (1996) stated that there is a high probability that post-1967 wells have been properly plugged. However, the insurance of a good plugging job does not guarantee the integrity of the well relative to CO_2. Cement plugs in well bores are always going to be a point of weakness in sequestration. Even wells abandoned to current standards cannot be guaranteed leak-free in the long term. It is not even certain that their long-term probability of leakage is smaller than that of wells drilled in the late 19th century, although short-term (decades) leakage probability is likely less. The mitigating factor in the Gulf Coast area is that open wells may benefit from their natural tendency to heave and close (e.g., Clark et *al.*, 2003). In any case, restricting the injection to a depth of 10,000 ft or deeper will increase the likelihood of having a comprehensive list of all wells possibly impacted because older wells are shallower.

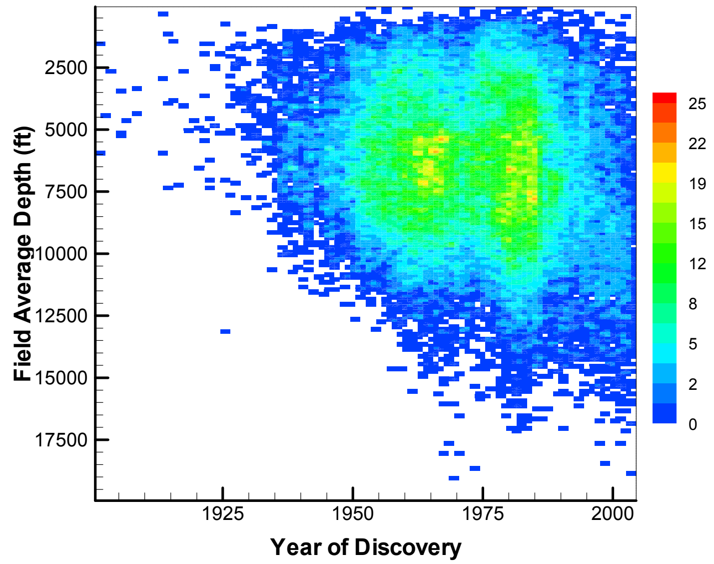


Figure 12. Average depth vs. year of discovery for fields of RRC districts 2, 3, and 4. Key is in number of fields / year / 100 ft

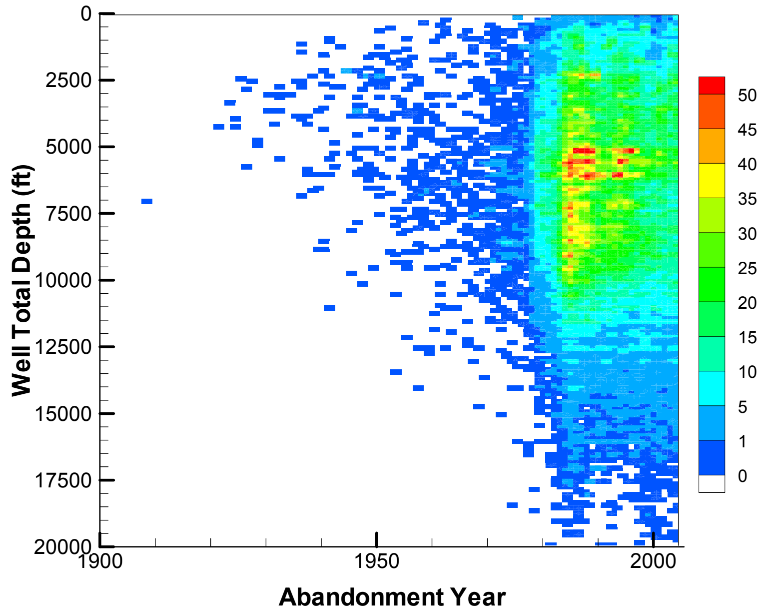


Figure 13. Well total depth distribution (Texas RRC districts 2, 3, and 4. Key is in number of wells / year / 100 ft)

Leakage

Few datasets compile well leakage information (this is also true for fault leakage), although numerous instances of anecdotal evidence exist. There have been several models (e.g., Celia et al., 2006; LeNeveu et al., this volume) exploring well leakage impact but they acutely lack representative input data. Paine et al. (1999), when investigating shallow groundwater and surface-water salinization problems in West Texas, concluded that a significant fraction came from leaking wells. A shallow formation (Coleman Junction Formation in the Permian Basin) located about ~800 ft bgs is artesian, which could be considered mimicking pressure increase due to CO_2 injection. Most of the wells are from 20-30's through the 60's. A total of 39 geophysical anomalies fits the profile of a leaking well and at least 718 wells are in the area. Approximately 39 out of 718 known wells are leaking or have leaked in the past (~5%). Leakage rates were unknown and are in general hard to characterize.

Permitting Implications

Siting Considerations

An important factor to consider in the siting of a carbon storage facility should be to avoid well bores that represent the most direct conduit to the USDW and the ground surface. It follows that the injection levels should be as deep as economically feasible. In the Texas Gulf Coast, the best way to achieve this goal is to establish the primary injection level below the total depth of most wells. Because porosity generally decreases with depth, there is an optimal depth to inject CO_2. In the Gulf Coast, that depth is in the vicinity of ~10,000 ft (Mark Holtz, personal communication). Similarly, most faults, particularly growth faults, do not reach the surface (with the exception of those accommodating accumulation in wedge "6" of Figure 1 and those major regional faults, located farther inland). Water wells are generally much shallower, generally above 2,000 ft, (Figure 14) and do not present a problem. The base of the USDW is variable but is generally located in the 2,000 – 3,000 ft range.

Leakage mechanisms are in essence identical to a "fill-and-spill" operational method in which multiple individual traps are successively filled. It can thus be argued that no leakage of stored CO_2 as such will occur until the plume has reached the base of the regional seal or even maybe the vicinity of the base of the usable quality water. Overall, capillary trapping is likely to be an efficient short term mechanism to control CO_2 leakage to USDW and beyond to the atmosphere. Capillary trapping as a leakage control mechanism will be acceptable only if the contacted volume is large enough to absorb a significant mass of the leaking plume, that is, if the heterogeneity of the sedimentary pile is large enough.

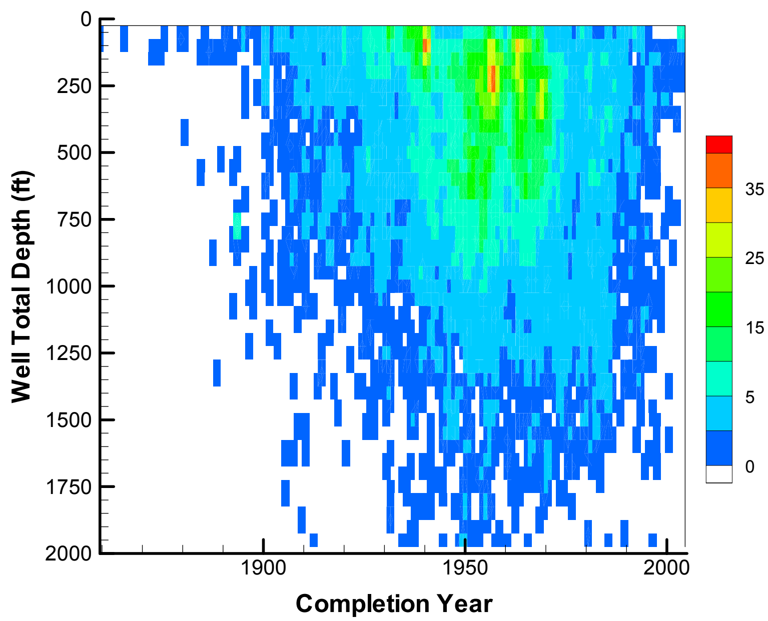


Figure 14. Total well depth vs. completion for water wells (data from TWDB). Key is in number of wells / year / 50 ft

Performance Based General Permit

Some EPA offices are questioning the adequacy of a fixed radius for traditional injection wells (Frazier et al., 2004), which can certainly be justified in the case of CO_2 injection. A fixed radius of influence seems impractical and would in most cases be larger than the 2.5 miles required by UIC Class I rules. The typical elongated shape of a trap does not fit well with a circular area of review. The usual requirement / assumption that the injectate not leave the injection horizon (Class I to III wells) is probably unreasonable (Nicot et al., 2006). The strong buoyancy of the CO_2 and the additional leakage pathway add a vertical dimension, in addition to the two customary lateral dimensions, to the area of review that truly becomes a "volume of review."

The large volumes to be injected will necessarily translate into some leakage. However, this does not mean that CO_2 cannot be safely sequestered underground. Even in case of leakage, imperfect geologic storage of the CO_2, currently emitted in the atmosphere and partially stored in ocean, would help in meeting the fundamental goal of carbon sequestration. This suggests that CO_2 injection should treated at the regional or at least subregional level allowing leakage in a statistical sense but whose exact locations may be hard to pinpoint before injection starts. States with possibly the help of federal agencies (USGS, EPA) would be responsible for developing those models. Individual operators would then apply, based on regional model guidance, for permits that would focus on relatively simpler modeling of specific injection parameters. The state of Texas has already had a successful experience implementing such a system for a sound management of ground water resources (TWDB, 2006). The participation of stakeholders and of other local entities is actively sought. It could be used as a starting point to develop a similar management model for CO_2 storage.

Acknowledgements

The Gulf Coast Carbon Center, Bureau of Economic Geology acknowledges support of this research by the Department of Energy Contract No. DE-FC25-04NT42210 as well as by industry partners and by the John A. and Katherine G. Jackson School of Geosciences, The University of Texas at Austin. Several individuals, including Paul Knox and Thet Naing, were instrumental in the success of this research.

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